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(71) Applicants
Jet Research Center, Inc.,
P.O. Box 246,
Arlington,
Texas 76010,
United States of America.
Brown & Root, Inc.,
P.O. Box 3,
4100 Clinton Drive,
Houston,
Texas 77001,
United States of America.
(72) Inventors
John Anthony Regalbuto,
James Elvin Dailey.
(74) Agents
A.A. Thornton & Co.,
Northumberland House,
303-306 High Holborn,
London WC1V 7LE.

(54) Method and apparatus for explosively joining tubes

(57) The method comprises forming a circumferential joint between two telescoped tubes (for example a pile and a jacket leg of a marine structure), in which an explosive charge at a predetermined location within the inner tube is detonated so as to cause plastic bulging of the inner tube and elastic (non-plastic) bulging of the outer tube. The annular space between the tubes is free of liquids, such that bulging of the inner tube causes the latter to contact the outer tube, preferably in the region of a circumferential groove (16) in the inner surface of the outer tube.

The apparatus comprises an elongate member (28) having thereon a carrier for an annular explosive charge (20) and means (26) for centralizing the carrier in the inner tube both in the operative position and during movement along the inner tube.

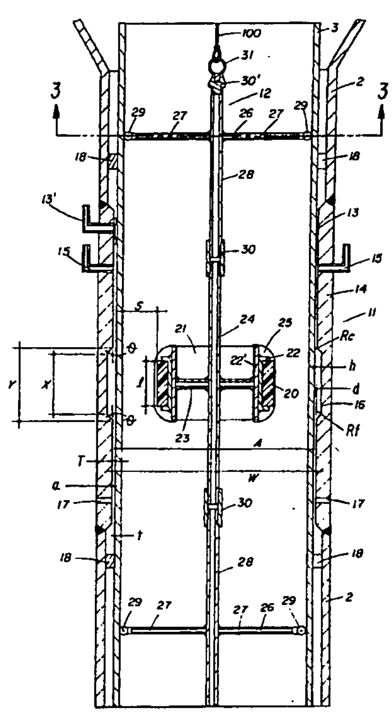

Fig. 2

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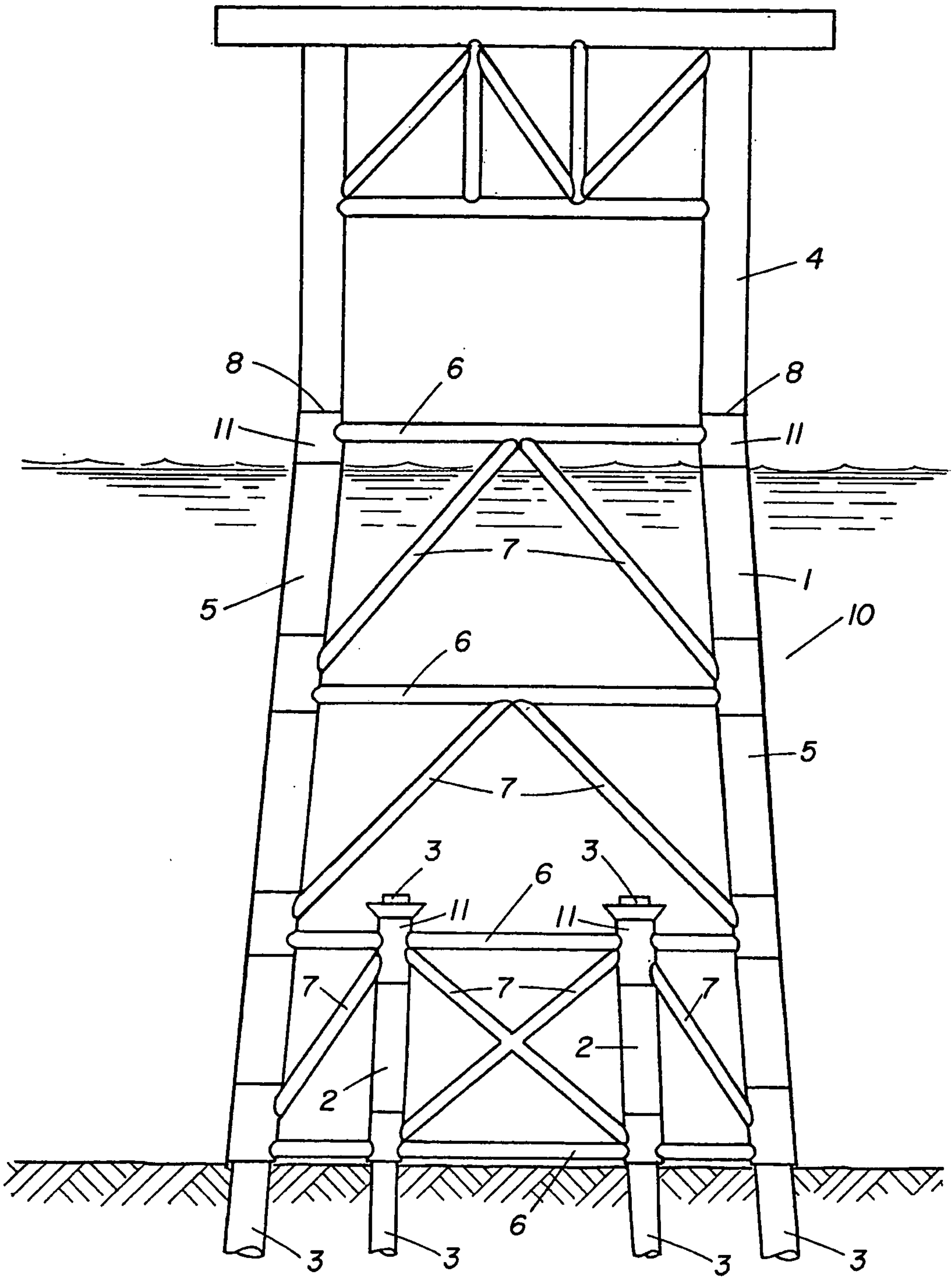

Fig. 1

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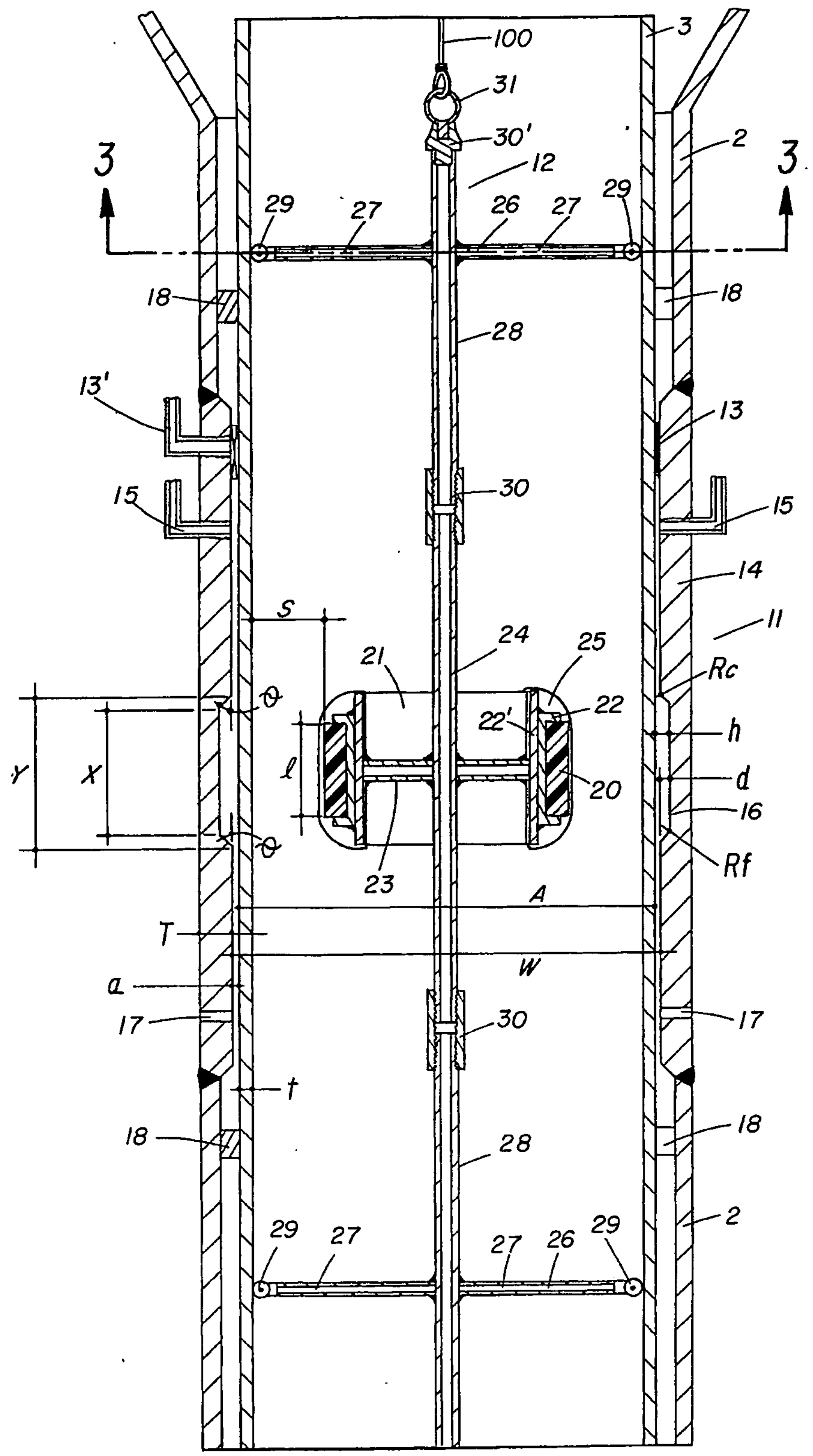


Fig. 2

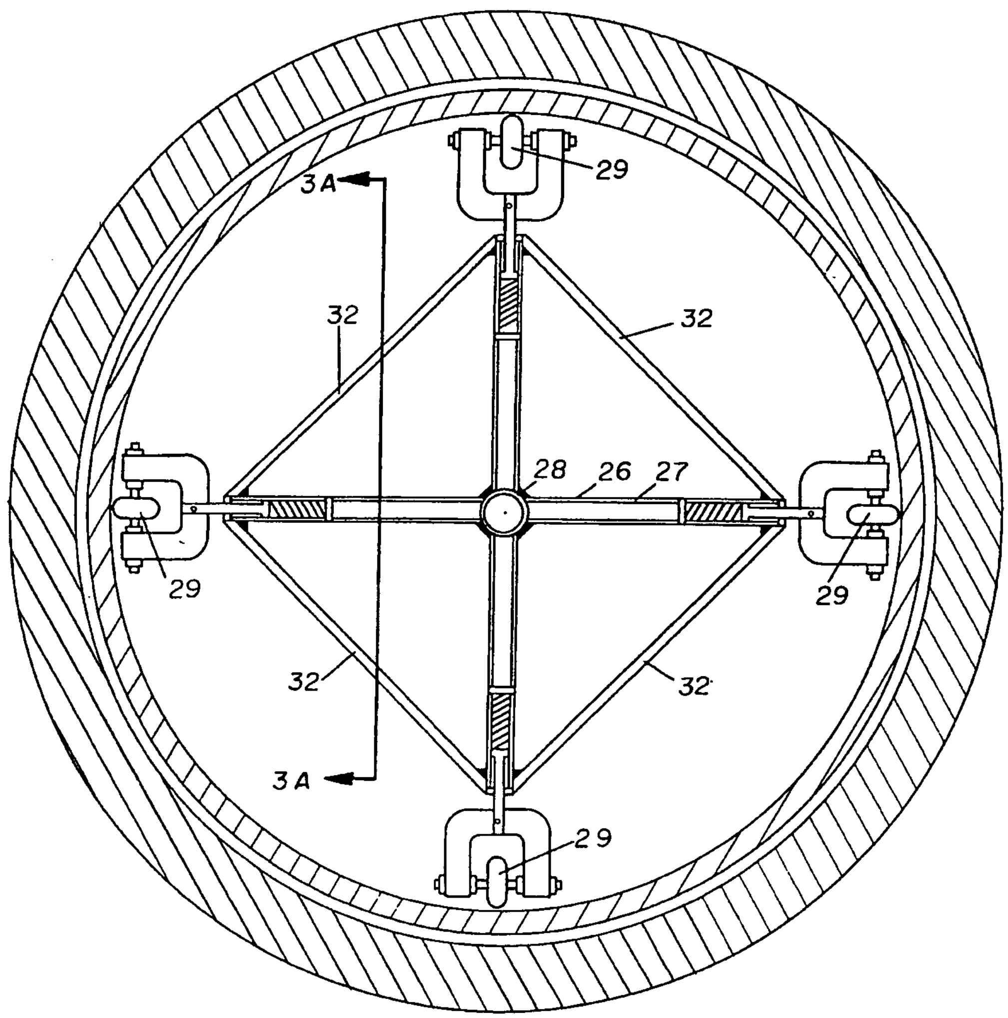


FIG. 3

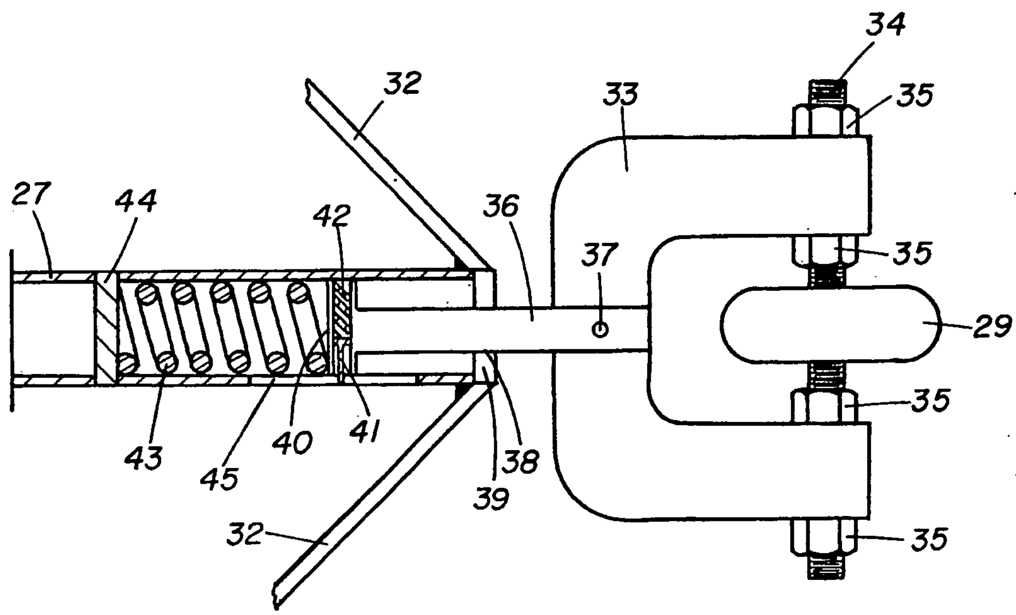
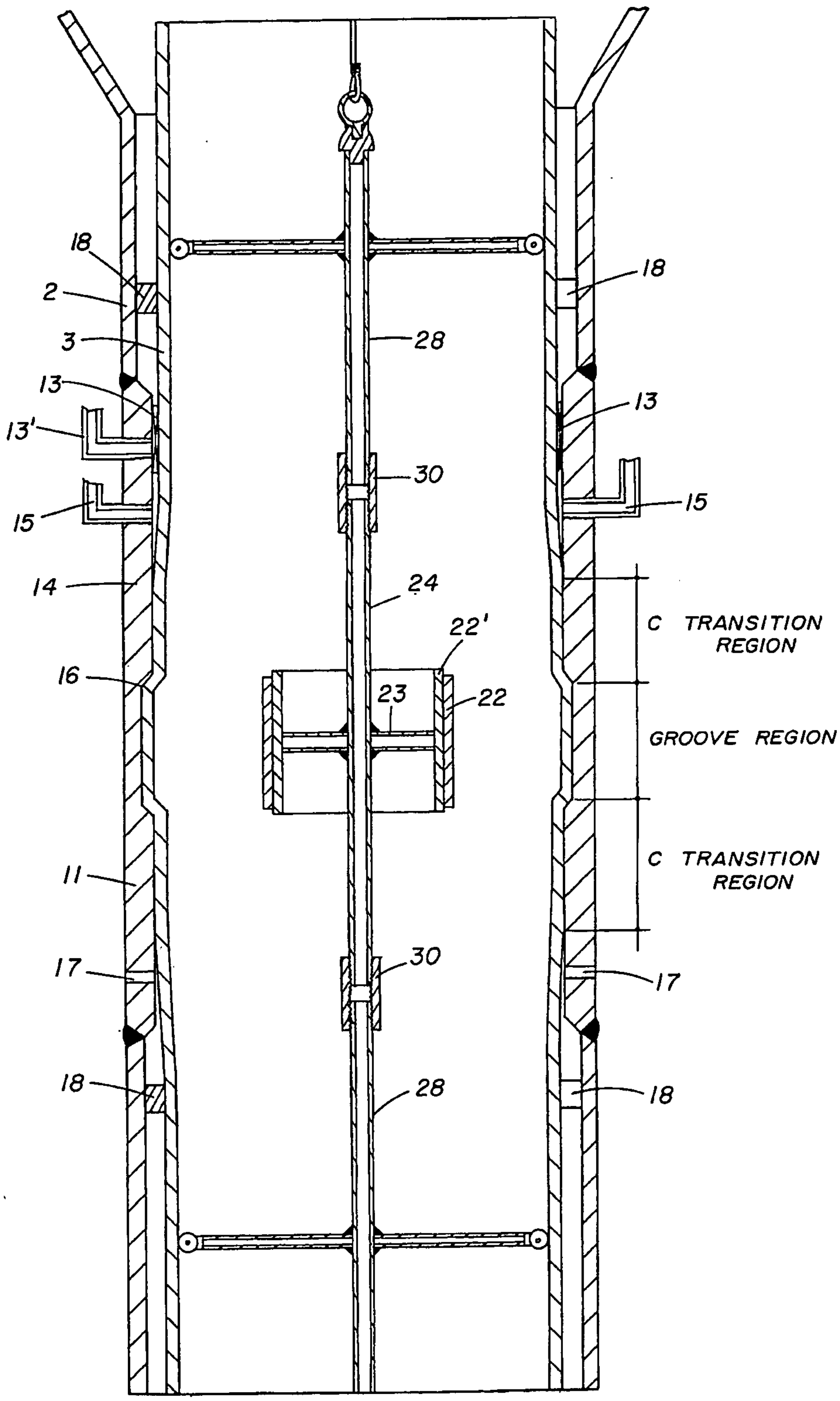


Fig. 3A



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3
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13'
15
14
16
11
17
18
28
30
24
22'
23
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28
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13
15
C TRANSITION REGION
GROOVE REGION
C TRANSITION REGION
17
18

Fig. 4

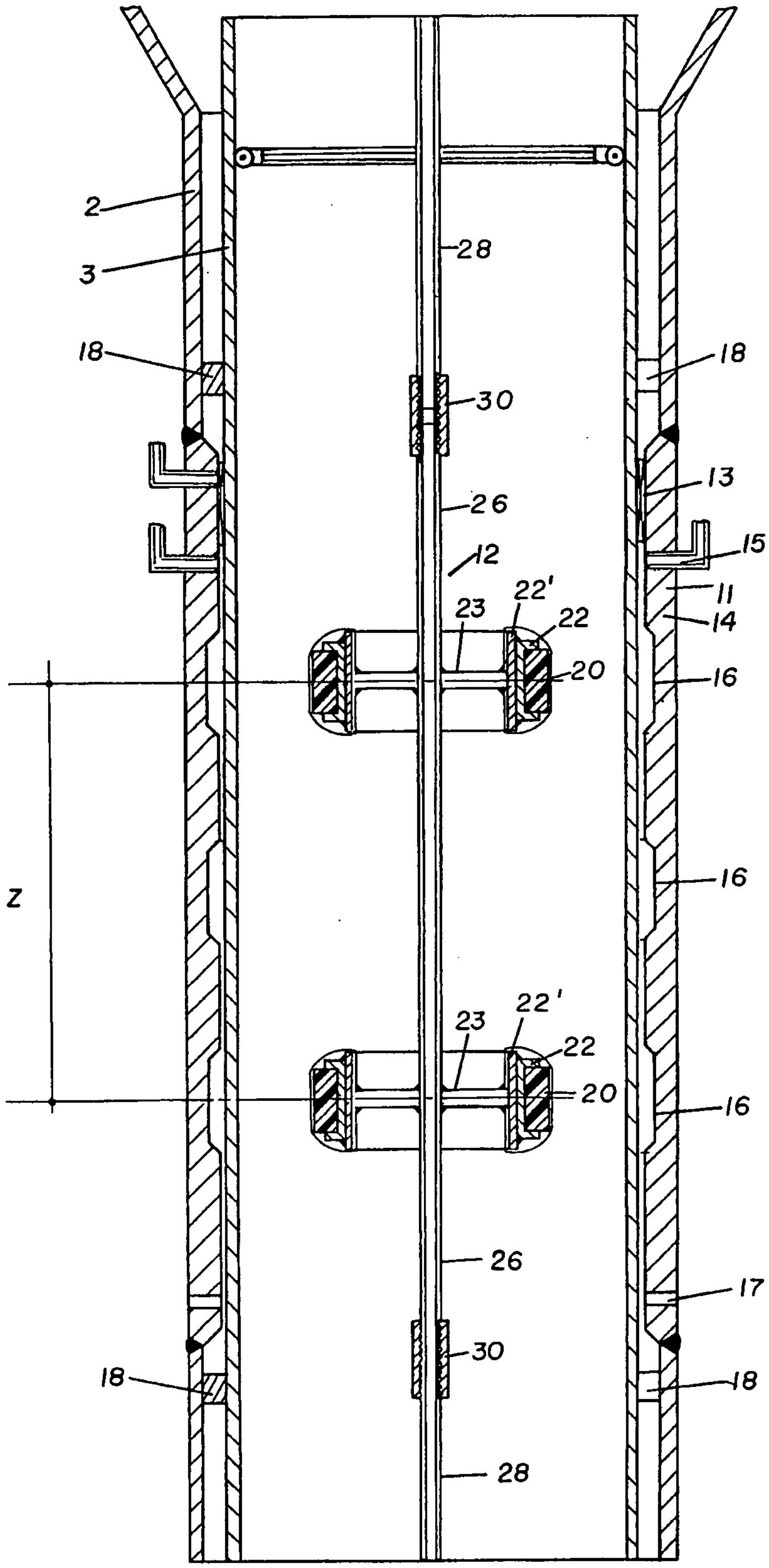

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FIG. 5

SPECIFICATION

Method and apparatus for explosively joining tubes

The present invention is concerned with a method of, and apparatus for, explosively forming at least one circumferential joint between two tubular members disposed one within the other, this method and apparatus being particularly useful in the construction of marine structures.

Generally, a marine structure used for the exploration and production of hydrocarbons comprises an underwater portion, comprising a jacket which is fabricated as a framework of tubular members, a plurality of piles driven into the sea bed, and a deck section set on top of the jacket after the piles have been secured to the jacket.

In such a marine structure, the jacket serves as a template or guide through which the piles are driven into the sea bed and then, after the piles have been driven and secured to the jacket, the jacket provides a strong framework to transmit and distribute loads imposed on the structure as a whole to the piles.

In shallow water, main piles driven through the jacket legs are normally sufficient to provide adequate support for such a marine structure, the main piles being generally connected to the jacket at the top of each jacket leg by welding the pile to the jacket leg before the deck section is set thereon. As the water depth increases, a point is reached where the main piles in the jacket legs are no longer sufficient by themselves to withstand the increasing horizontal shear forces and overturning moments imposed on the structure. Additional support for the marine structure is then required which is usually provided in the form of skirt piles arranged about the base of the structure.

Rather than extending to the top of the jacket, skirt piles are usually truncated at some distance bove the sea bed for two primary reasons. First, the skirt piles are not needed for structural integrity of the jacket and, second, additional members, such as skirt piles, extending to the top of the jacket into the wave zone of the jacket would attract more wave forces, thereby increasing the stresses in adjacent members.

Since the connection between the skirt around the jacket and the pile to the skirt is made underwater, the procedures used to make the pile to skirt connection are an important consideration in the design of the marine structure.

The conventional method of connecting the skirt piles to the jacket skirt comprises filling the annulus between the skirt pile and a skirt sleeve with grouting material. However, the use of a grout is expensive and it is difficult to ascertain the quality of the grouted connections.

Several alternative methods of forming pile-to-jacket connections have therefore been proposed. For example, U.S. Patent 3,555,831 describes a process in which a tool is lowered into the cylindrical casing (which supports a drilling platform) having a piling therein, the tool being actuated to form a plurality of mechanically cold worked swaged connections between the casing and the piling. If the tool malfunctions, it can be retrieved and repaired.

Another such method utilizing a tool permanently secured to the jacket to mechanically grip the piling is described in U.S. Patent 4,052,861, in which the tool is inflated to temporarily or permanently grip the piling by means of a plurality of flexible fingers which engage the outer periphery of the piling. However, since the tool is permanently installed, if the tool malfunctions it cannot be retrieved for repair. Also, the fatigue life under long term cyclical loading of the connection between the piling and jacket due to the concentrated stresses created by the localised engagement of the outer periphery of the piling by the flexible fingers of the tool is presently unknown and must be empirically estimated.

Yet another method has been used in which a tool is hydraulically actuated to permanently expand the piling into an annular groove in the interior of the jacket leg or pile sleeve of the jacket. While the tool is relatively easy to operate, the swaged connection between the pile and jacket exhibits lowered fracture toughness during loading of the marine structure.

However, in comparison, if a connection between two members can be substantially instantaneously formed using a high energy source, the connection may not exhibit as much fracture toughness sensitivity. It is well known to use the application of substantially instantaneous high amounts of energy, such as the use of an explosive, to bond one metal to another base metal, for example, as described in U.S. Patents 3,137,937; 3,140,537 and 3,264,731.

It is also well known to join one tubular member to another tubular member, by means of explosives, for example, as described in U.S. Patents 2,367,206; 3,160,949; 3,432,192; 3,572,768 and 3,661,004.

It is further well known to use explosives to join one tubular member to another utilizing a backup member to contain the deformation of the tubular members. For example, such techniques are described in U.S. Patents 2,779,279; 3,206,845; 3,263,323; 3,434,194 and 3,710,434.

It is also well known to explosively join one tubular member to another in the laying of marine pipelines, for example, as described in U.S. Patent 3,720,069.

A further known method of joining tubular members to one another, underground, through the use of explosives, involves firing projectiles from the interior of one tubular member through the wall thereof into and through the wall of the other tubular member while forming outwardly extending anchoring bumps in the walls of the tubular members. For example, such a technique is described in U.S. Patent 4,123,913.

We have now developed an improved method of forming at least one circumferential joint between two tubular members disposed one within the other, which comprises detonating at least one explosive charge,

the or each charge being at a predetermined location within the inner tubular member so as to cause the latter to plastically expand radially outwardly into engagement with the inner surface of the outer tubular member which is also expanded outwardly by detonation of the or each charge but substantially only elastically, the annular space between the inner and outer tubular members at the or each predetermined location being substantially free of incompressible media.

The method according to the invention is simple and economical to use and enables grouting to be dispensed with. Furthermore, because the outer tubular member is not plastically deformed, it is believed that undesirable stress properties at the joint may be avoided. Highly concentrated stress patterns can be avoided, thereby facilitating accurate mathematical prediction of the fatigue life of the circumferential joint under prolonged cyclic loading.

The method according to the invention avoids the need for a back-up member or anvil around the outer tubular member.

The present invention also comprises apparatus for explosively forming at least one circumferential joint between two tubular members disposed one within the other, which comprises an elongate member having thereon at least one annular carrier, the or each said carrier being constructed and arranged to carry an annular explosive charge for insertion into and movement along the inner tubular member, and means for centralising the or each annular carrier in the inner tubular member, both in the respective operative position for explosive forming and during movement along the inner tubular member.

The annular carrier in such apparatus can be readily removed from the inner tubular member prior to detonation of the explosive charge, if a malfunction occurs.

In the following description, reference will be made to the accompanying drawings, in which:

Figure 1 is a view of an illustrative marine structure;

Figure 2 is a section of part of Figure 1, at a predetermined location at which a circumferential joint is to be explosively formed;

Figure 3 is a cross-section of the arrangement of Figure 2, taken along the line 3-3;

Figure 3A is an enlarged sectional view of part of Figure 3, taken along the line 3A-3A;

Figure 4 is similar to Figure 2, showing the tubular members after they have been explosively joined; and

Figure 5 is a section of a modification of the arrangement shown in Figure 2;

Referring to Figure 1, a marine structure 10 is shown. The marine structure 10 comprises a jacket 1 having skirt pile sleeves 2 thereon, piles 3 driven through the jacket into the sea bed, and a deck 4 above the surface of the body of water in which the marine structure 10 is installed.

The jacket 1 comprises a plurality of jacket legs 5, each having a pile 3 driven therethrough into the sea bed interconnected by a plurality of horizontal braces 6 which are also interconnected by a plurality of angular braces 7.

The skirt pile sleeves 2 comprise tubular members secured to the jacket 1 by means of a horizontal brace 6 and angular braces 7. The skirt pile sleeves 2 each have a pile 3 driven therethrough into the sea bed.

The deck 4 is secured to the tops 8 of the jacket legs 5, by welding, for example, to form the marine structure.

Referring to Figure 2, there is shown a skirt pile sleeve 2 having a pile 3 driven therethrough of the marine structure 10, a tubular member or can 11, explosive carrier member 12, seal means 13 and inlet port 13'.

As shown, the tubular member or can 11 comprises a heavy walled or thick tubular member 14 having an inlet port 15 in the upper portion thereof, a circumferential annular groove or socket 16 in the interior thereof, and an outlet port 17 in the lower portion thereof.

The tubular member 11 further contains a seal 13 on the interior surface thereof to sealingly engage the pile 3 driven therethrough. The seal 13 may be any commercially available seal capable of forming a reliable seal with the pile 3 after the pile 3 has been driven therethrough. The seal 13 may, alternatively, be located above the tubular member 11 at any convenient location. Examples of suitable seals 13 which may be utilized are described in U.S. Patents 3,468,132 and 4,047,391.

The tubular member 11 may be secured at any point in either the jacket legs 5 or skirt pile sleeves 2, although it is preferred that they be installed at the intersection of the horizontal 6 and angular 7 braces with the jacket legs 5 and skirt pile sleeves 2.

Also shown in Figure 2, located on either side of the tubular member 11, are centralizer means 18 which are used to centre the pile 3 in the skirt pile sleeve 2.

The explosive carrier member 12 as shown in Figure 2 comprises a carrier body 21 having an annular explosive charge 20 secured thereto, within arcuate annular channel members 22 which are, in turn, secured to outer annular carrier 22' of carrier body 21. The outer annular carrier 22' is retained on central mandrel 24 of the carrier body 21 by means of struts 23. The struts 23 may be of any convenient cross-sectional shape and of any type material sufficient to support the explosive charge 20.

Typically, the explosive charge 20 is toroidal or annular in configuration and is installed on the explosive carrier member 12 by attaching means 25.

The explosive carrier member 12 further comprises centralizer means 26 located on either side of the explosive charge 20. The centralizer means 26 may be of any convenient type, although a plurality of radial struts 27 connected to a central elongate member 28 having wheels 29 thereon are preferred (see also Figure 3).

The centralizer means 26 may be secured to the central mandrel 24 of the explosive charge carrier 21 by

any convenient easily releasable means, such as a threaded coupling 30.

The explosive carrier member 12 additionally comprises plug and lifting means 30' and 31 respectively to provide a means by which a line 100 can be attached to the explosive carrier member 12 to position the explosive carrier member in a jacket leg 5 or skirt pile sleeve 2.

Also included on the explosive carrier member 12 (not shown in Figure 2) is an indicator means, such as a commerically available ultrasonic indicator for indicating the position of the explosive charge carrier member 12 within the pile 3 (the correct operative position being substantially centered about the annular groove 16 in the tubular member 11), and a detonator having suitable actuation means to initiate explosion of the explosive charge 20.

Referring to Figure 3, the centralizer means 26 is shown in more detail; the centralizer means 26 comprises a plurality of radial struts 27 secured to a central elongate member 28 and interconnected about their outer ends by braces 32.

Referring to Figure 3A, the details of the wheels 29 and their interconnection with the centralizer means 26 can be seen. Each wheel 29 is retained on a U-shaped member 33 by a threaded bolt 34 having nuts 35 thereon. The U-shaped member 33 is secured to a rod 36 by a pin 37. The rod 36, in turn, passes through bore 38 in the end 39 of strut 27 and has a plate 40 having spring actuated pin 41, actuated by spring 42. The plate 40 on rod 36 is biased outwardly by a compression spring 43, which is retained within strut 27 and has one end thereof bearing against strut plug 44 while the other end bears against plate 40. To prevent the wheel 29 from rotating about the axis of rod 36 when the centralizer means 26 engages the inner surface of the skirt pile sleeve 2 or jacket leg 5, the pin 41 engages a slot 45 in strut 27 and slides therein.

When the centralizer means 26 engages the inner surface of the skirt pile sleeve 2 or jacket leg 5 when the explosive carrier member 12 is being lowered therein, the wheels 29 of the centralizer means 26 are biased into engagement with the skirt pile sleeve 2 or jacket leg 5 by compression spring 43.

Arrangements other than the illustrated centralizer means 26 may be used to centre the explosive charge carrier 21 in the skirt pile sleeve 2 or jacket leg 5, if desired.

Referring again to Figure 2, the procedure for determining the various relationships between the tubular member 11, explosive carrier mmber 12 and the pile 3 will now be discussed.

The internal diameter "W" of the heavy walled tubular member 14 is determined by taking the outside diameter "A" of the pile 3 and adding to that dimension twice the annular space "a" between the internal surface of the tubular member 14 and the external surface of the pile 3. It should be noted that the outside diameter of the pile 3 will be determined by the pile driving and operational loading upon the pile. Similarly, it should be noted that the annular space "a" between the tubular member 14 and pile 3 will be determined by the minimum clearance required between the tubular member 14 and pile 3 to facilitate the driving of the pile 3 through the tubular member 14. Also, the thickness "t" of the pile wall will be determined by the pile driving and operational loading upon the pile 3.

The bulge height "h", the distance between the outside surface of the unexpanded pile 3 and the bottom surface of the annular groove 16 is preferably in the range of $0.02A \leq h \leq 0.25A$, more preferably in the range of $0.04A \leq h \leq 0.16A$ and most preferably in the range of $0.08A \leq h \leq 0.12A$. The bulge height "h" must be greater than the annular space "a".

The depth of the annular groove 16 in the heavy walled tubular member 14, which is the distance "d" between the internal surface of the tubular member 14 and the bottom of the annular groove 16, is calculated by the equation:

$$d = h - a$$

The thickness "t" of the tubular member 14 is determined after the dimension "d" has been calculated based upon the loading of the tubular member 14. However, the thickness "t" of the tubular member 14 should preferably be in the range of

$$10 \leq \frac{W}{t} \leq 40$$

and more preferably in the range of

$$30 \leq \frac{W}{t} \leq 35.$$

The length "Y" of the annular groove 16 along the internal surface of the tubular member 14 is determined by the general equation:

$$O \leq Y \leq 2\ \frac{3\pi}{4\beta}$$

$$\text{where: } \beta = \left[\frac{12(1-\nu^2)}{A^2t^2}\right]^{1/4}$$

and ν is Poisson's ratio.

Poisson's ratio for steel is 0.27; therefore, the general equation for groove length "Y" when the material of tubular member 14 is steel, reduces to the equation:

$$0 \leqslant Y \leqslant 2 \left(1.83\sqrt{\frac{At}{2}}\right)$$

The preferred values of "Y" are values which occur in the range of from about $3\pi/4\beta$ to about $1.5\pi/\beta$. For steel, the preferred values reduce to values in the range of from about $1.29\sqrt{At}$ to about $2.58\sqrt{At}$.

The length "X" along the bottom of the annular groove 16 in the tubular member 14 is determined by the groove angle θ (by which we mean herein the angle between the groove end surface and the imaginary continuation of the inner surface of the tubular member), which is preferbly less than 90°, more preferably in the range of 5° to 60° and most preferably in the range of 20° to 45°. If the groove angle θ is too small, such as less than 7.5°, the high energy formed connection may be flexible and tend to yield. However, if the groove angle θ is too large, such as from 60° to 90°, the pile may split upon the explosive formation of the circumferential joint.

The corner radius "R_c" at the intersection of the shoulder of the annular groove and the internal surface of the tubular member 14 should preferably be in the range of

$$0.5 \leqslant \frac{R_c}{t} \leqslant 16$$

and more preferably R_c should approximately equal t, as defined above.

Similarly, the radius "R_f", the fillet radius at the intersection of the groove end surface or shoulder and the bottom of the annular groove 16 should be equal to the radius "R_c".

Of the radii "R_c" and "R_f", the radius "R_c" is more critical since if it is too small, the pile 3 may fracture upon forming the circumferential joint between the pile 3 and tubular member 14.

Finally, the number of annular grooves 16 required to carry the load placed upon the pile 3 is a function of the permissible load "L" per groove which may be defined by the equation:

$$L = \frac{[f_y t^2 \pi A \theta]}{d} (\tfrac{1}{2} \sin \theta)$$

where f_y is the yield strength of the pile material.

The permissible load "L" per annular groove 16 can be optimized by varying the distance "d", the depth of the annular groove 16 in the tubular member 14, and θ, the groove angle. It should be remembered that "A" and "t" are previously determined by the pile driving and operational loading upon the pile.

The number of annular grooves 16 required to transfer the operational loading to the pile 3 may be determined by dividing the required operational loading of the pile 3 by the permissible loading "L" of each annular groove 16. If it is determined that more than one annular groove, 16, is required per pile, then the distance between immediately adjacent grooves, "groove separation", is preferably at least a quarter of the groove length, i.e., 0.25Y, since a groove separation of less than one quarter of the groove length (0.25Y) may cause the pile to buckle between adjacent grooves upon loading. In a more preferred embodiment, the groove separation is approximately equal to groove length, Y.

The charge standoff distance "S", the distance between the outer surface of the explosive charge 20 and the internal surface of the unexpanded pile 3 can be equal to one-fifth (⅕) of the internal pile diameter or, alternatively,

$$S = \frac{A - 2t}{5}$$

The explosive charge 20 should not contact the internal surface of the unexpanded pile 3, because undesired damage to the pile, such as spalling and fracturing, could occur upon detonation of the charge. Thus, charge standoff "S" is greater than 0. Where "S" approaches 0, a buffer such as an elastomer, may be placed between the explosive charge 20 and the internal surface of pile 3.

Since explosive charge 20 may be in a concentrated form, such as a line charge or a spherical charge, charge standoff distance "S" may approach a dimension equal to the inside radius of pile 3, e.g.

$$S < \frac{A - 2t}{2}$$

Such concentration charges are not desired, because bulge-forming efficiency decreases as standoff distance increases.

It is thus preferred that charge standoff distance "S" be in the range of from about

$$\frac{A - 2t}{5} \text{ to about } \frac{A - 2t}{3}.$$

The length "ℓ" of the surface of the explosive charge 20 is preferably in the range of from 0.25Y to 1,33Y, more preferably about 0.625Y. When the charge standoff distance "S" is small, the explosive length "ℓ" is large. Thus, when "S" is at its minimum, "ℓ" is preferably equal to about 1.33Y.

The weight and geometry of explosive charge 20 can be calculated separately.

The estimation of total deformation energy, "E_D", required to form the circumferential joint in the method according to the invention is based on a consideration of the final connection geometry, which, referring to Figure 4, is characterised as consisting of a groove region and two transition regions. In Figure 4, the exterior surface of pile 3 is shown after deformation to be pressed against the interior surface of tubular member 14 for some distance in "transition regions" on both sides of annular groove 16. The pile in the "groove region" is shown to be crimped tightly over the outside corners of groove 16 and pressed against the centre portion of groove 16.

The equation for calculation of total deformation energy, "E_D", is, therefore,

$$E_D = E_{D1} + E_{D2} + E_{D3}$$

wherein: E_{D1} is the energy required to expand or "bulge" the pile into the groove region; E_{D2} is the energy required to expand the outside diameter of pile 3 to the inside diameter of tubular member 14 in the transition region; and E_{D3} is the residual strain energy in the tubular member 14.

The deformation energy equations set out below are taken from a general expression given in Figure 2-48, page 65 of Bruno, E.J., Editor, *High Velocity Forming of Metals*, American Society of Tool and Manufacturing Engineers, Dearborn, Michigan, 1968.

The equations for E_{D1}, E_{D2} and E_{D3} are set out below:

$$E_{D1} = (2\pi r_2)\,(Y)\,(t)\,(Q)$$
$$E_{D2} = (2\pi r_3)\,(2C)\,(t)\,(Q)$$
$$E_{D3} = (2\pi r_5)\,(Y)\,(T\text{-}d)\,(Q)$$

wherein:

"Y" is the groove length of annular groove 16, previously defined (See Figure 2);

"t" is the wall thickness of pile 3, previously defined (See Figure 2);

"Q" is the general expression

$$\left(\frac{K}{n+1}\right)\left(e^{-0.9\varepsilon}\right)\left(\varepsilon^{n+1}\right);$$

"C" is the length of the transition region, previously defined (See Figure 4);

"T" is the thickness of the heavy walled tubular member 14, previously defined (See Figure 2);

"d" is the depth of annular groove 16, previously defined (See Figure 2);

"r_1" is the unexpanded inside radius of pile 3 which is defined as

$$\frac{A-2t}{2} \text{ (See Figure 2);}$$

"r_2" is the expanded inside radius of pile 3 in the groove region which is defined as $r_1 + h$ (See Figure 2);

"r_3" is the expanded inside radius of pile 3 in the transition regions, which is defined as $r_1 + a$ (See Figure 2);

"r_4" is the unexpanded inside radius of tubular member 14 in the groove region, which is defined as $r_1 + t + h$ (See Figure 2); and

"r_5" is the expanded inside radius of tubular member 14 in the groove region, which is defined as $r_4 + k$.

The terms of the general equation

$$\text{"Q"} = \left(\frac{K}{n+1}\right)\left(e^{-09\varepsilon}\right)\left(\varepsilon^{n+1}\right)$$

are defined as follows:

"K" and "n" are material constants in the flow stress power law relating true stress to true strain wherein $\sigma = K\varepsilon^n$. Values for "K" and "n" can be found in Table 3.1, page 69 of Ezra, A.A., *Principles and Practice of Explosive Metalworking*, Volume I, Industrial Newspapers Ltd., London, 1973. For steel values of "K" and "n" which can be used herein for estimating purposes are 100,000 psi and 0.24, respectively.

The term "ε", appearing in the general equation "Q", is the material strain involved in each of the equations for E_{D1}, E_{D2} and E_{D3}. Therefore, in accordance with the well known definition for strain, ε is the ratio of the increase in a given radius to the initial value of the given radius. Accordingly, in the equation for E_{D1}, the strain factor ε is defined as h/r_1; in the equation for E_{D2}, the strain factor ε is defined as a/r_1; in the equation for E_{D3}, the strain factor ε is defined as k/r_4.

With respect to ε in the equation for E_{D3}, the value for "k", the increase in radius r_4, is not defined. Accordingly, in order to assure that tubular member 14 remains in elastic deformation, an allowable average circumferential strain in the groove region in tubular member 14 is specified. The equation for r_5 thus reduces to $r_5 = r_4\,(1+)$. To thus obtain the required elastic deformation, it is believed that ε for E_{D3} can safely

be specified to be about 2% (i.e. 0.02 inches/inch).

With respect to the equation for E_{D2}, above, the value of "C"cannot be exactly defined for there is no known existing method of predicting the length of metal contact in the transition regions (Figure 4). However, experimental evidence reveals that the transition region extends less than one pile diameter on either side of the groove region. Accordingly, the value of "C" for estimating purposes is believed to be in the range of from about 50% of the outside diameter of pile 3 to about 100% of the outside diameter of pile 3 and preferably about 75% of the outside diameter of pile 3, i.e. 0.5 "A" to "A"; preferably 0.75 "A".

To calculate the weight "M" of the explosive required to form a single high energy formed connection, the weight "M" is defined as:

$$M = \frac{E_D}{F} \frac{1}{\text{(Specific Energy of the Explosive Used)}}$$

where F is an estimated forming efficiency from Figure 2-49 of the *High Velocity Forming of Metals,* American Society of Tools and Manufacturing Engineers, E.J. Bruno, Ed., Dearborn, Michigan, 1968.

Operation

To form a circumferential joint between a pile 3 and tubular member 11 in the method according to the invention the pile 3 is first driven to the desired depth in the sea bed and the pile 3 is then usually, although not necessarily, truncated to allow the easy insertion of the explosive carrier member 12 therein.

The explosive carrier member 12 is lowered into the pile 3 by a suitable lifting means (not shown) such as a crane on a derrick barge, until the explosive charge 20 is substantially centered about a plane passing through the centre of the annular groove 16 in the tubular member 14.

Once the explosive charge 20 is centered about the annular groove 16 in the tubular member 14, compressed air or gas is introduced through inlet port 13', causing seal 13 to sealingly engage the exterior surface of the pile 3. Next, compressed air or gas in injected through inlet ports 15 in the tubular member 14 to expel the water contained in the annulus between the tubular member 14 and pile 3 through the outlet ports 17. Once the annulus between the tubular member 14 and pile 3 has been substantially free of liquid in the area surrounding the annular groove 16, the explosive charge 20 may be detonated to form the circumferential joint.

The tubular member 14 should be merely in elastic deformation since the explosive charge 20 is sized to merely plastically deform the pile 3 but not the tubular member 14 when the annulus between tubular member 14 and the pile 3 is substantially free of liquid. It is important to have the annular space between the tubular member 14 and pile 3 substantially free of water (and other incompressible media) so that a compressible medium is present in the annular space, or else the tubular member 14 would be plastically deformed like the pile 3, thereby impairing the strength of the circumferential joint. Plastic deformation of tubular member 14 is also avoided by carefully designing the tubular member 14 and the judicious selection of ductile material for the tubular member 14 and pile 3, as well as the proper size of explosive charge 20.

After the formation of the circumferential joint, the carrier member 12 can be retrieved from the interior of the pile 3 and carrier body 21, arcuate annular channel members 22, outer annular carrier 22' and central mandrel 24 can be replaced by another carrier member having an explosive charge 20 thereon.

The carrier member 12 can then be re-used any number of times so long as the threaded couplings 30 are not damaged and adequately support and release the central mandrel 24 from central elongate member 28.

If desired, the portion of the pile sleeve 2 below the tubular member 11 may be omitted since that portion of the pile sleeve serves only as the connection point for the horizontal brace 6 and angular brace 7, which may be otherwise connected or omitted depending upon the design of marine structure 10. If the portion of the pile sleeve 2 below the tubular member 11 is omitted, the marine structure may be more economical to construct since less material may be used.

Referring to Figure 5, a second embodiment of the present invention is shown. In this embodiment of the present invention, three circumferential joints are made between the tubular member 14 and pile 3 by means of an explosive carrier 12 having two explosive charges 20 thereon.

The various dimensions of the pile 3, tubular member 14 and explosive charges 20 may be calculated as if only one joint were to be made between the pile 3 and tubular member 14 by each explosive charge 20.

However, when two explosive charges 20 are used, if careful attention and consideration are given to the location of the annular grooves 16 in the tubular member 14, three circumferential joints between the tubular member 14 and pile 3 can be formed using only two explosive charges 20.

Thus, to form three circumferential joints using only two explosive charges 20 on the explosive carrier 12, the two explosive charges 20 must be substantially centered about planes passing through the centres of the outer two annular grooves 16 in the tubular member 14 and the distance "Z" between the centre of the two outer grooves 16 can be substantially equal to the external diameter "A" of the pile 3. The distance between the centre of two adjacent grooves is substantially equal to A/2 and the groove length "Y" is preferably not less than A/4.

Upon substantially simultaneous detonation of the explosive charges 20, the pile 3 is directly deformed into the outer annular grooves 16 in the tubular member 14 by shock waves, while the pile 3 is deformed into the centre annular groove 16 in the tubular member 14 by the combined effect of the shock waves from the two explosive charges 20. The combined effect of the shock waves from the explosive charges 20 is a shock

wave whose pressure can be from two to eight times the pressure from a single explosive charge 20, depending upon the proximity of the explosive charges 20 on the explosive carrier 12.

The spacing of the explosive charges 20 on the explosive carrier 12 is critical to prevent plastic deformation of the tubular member 14 in the vicinity of the centre annular groove 16. Should the distance "Z" between the outer annular grooves 16 be substantially less than the external diameter "A" of the pile 3, the combined effect of the shock waves emanating from the explosive charges 20 would be sufficiently great to cause plastic deformation not only of the pile 3 but also of the tubular member 14 in the vicinity of the centre of annular groove 16.

It is sometimes important to have the pile (inner tubular member) substantially centered in either the skirt pile sleeve or jacket leg (outer tubular member); otherwise, the circumferential joint may not be uniform about the skirt pile sleeve or jacket leg. However, if the pile is offset in either the skirt pile sleeve or the jacket leg, a satisfactory circumferential joint can be formed by offsetting the explosive carrier member within either the skirt pile sleeve or jacket leg to compensate for the eccentricity of the pile within either the skirt pile sleeve or jacket leg.

Finally, it is generally important to have the explosive charges substantially centered about a plane passing through the centre of the annular groove in the tubular member secured to the jacket leg or skirt pile sleeve in order to ensure that the circumferential joint is satisfactory.

Although the method according to the present invention has been described with respect to forming circumferential joints between either the pile and skirt pile sleeve or the pile and jacket leg of a marine structure, the method can be used to join any two tubular members in either atmospheric conditions or liquid environments.

CLAIMS

1. A method of forming at least one circumferential joint between two tubular members disposed one within the other, which comprises detonating at least one explosive charge the or each charge being at a predetermined location within the inner tubular member so as to cause the latter to plastically expand radially outwardly into engagement with the inner surface of the outer tubular member which is also expanded outwardly by detonation of the or each charge but substantially only elastically, the annular space between the inner and outer tubular members at the or each predetermined location being substantially free of incompressible media.

2. A method according to claim 1, in which the inner surface of the outer tubular member has a circumferential groove at the or each predetermined location, the or each groove having a circumferential bottom surface and first and second circumferential end surfaces, whereby, on detonation of the or each charge, the inner tubular member is deformed into the or each respective groove into contact with the or each circumferential bottom surface.

3. A method according to claim 2, in which the or each charge is located symmetrically about a plane sectioning the or each respective groove.

4. A method according to claim 2 or 3, in which the or each groove is symmetrical about a plane perpendicular to the longitudinal axis of the outer tubular member.

5. A method according to any of claims 2 to 4, in which the or each bottom surface of the or each respective groove has a longitudinal dimension, parallel to the longitudinal axis of the outer tubular member, of not more than

$$2\left(\frac{3\pi}{4\beta}\right) \text{ in which}$$

$$\beta = \left[\frac{12(1-\nu^2)}{A^2t^2}\right]^{1/4}$$

in which ν is Poisson's ratio,
A is the outside diameter of the inner tubular member, and
t is the wall thickness of the inner tubular member.

6. A method according to claim 5, in which said tubular members are of steel, and said longitudinal dimension is not more than

$$2\left(1.83\sqrt{\frac{AT}{2}}\right)$$

where A and t are as defined in claim 5.

7. A method according to claim 5 or 6, in which there are at least two said grooves, the longitudinal spacing between said grooves being at least one quarter of said longitudinal dimension.

8. A method according to claim 7, in which there are three said grooves.

9. A method according to any of claims 2 to 8, in which the intersection of the first circumferential end surface with the radially inward portion of the inner surface of the outer tubular member is defined by the expression

$$0.5 \leqslant \frac{R_c}{t} \leqslant 16$$

in which t is as defined in claim 5 and R_c is the radius of said intersection.

10. A method according to any of claims 2 to 9, in which the groove angle θ (as defined herein) of the first end surface is not more than 90°.

11. A method according to any of claims 2 to 10, in which the groove angle θ (as defined herein) of the second end surface is not more than 90°.

12. A method according to claim 10 or 11, in which the maximum load to which the or each groove can be subjected to is defined by the expression:

$$L = \frac{(f_y t^2 \pi A \theta)}{d} \quad (\tfrac{1}{2} \sin \theta)$$

wherein:

L = maximum load per groove
f_y = yield strength of the material of the inner tubular member
t = wall thickness of the inner tubular member
A = outside diameter of the inner tubular member
θ = groove angle (as defined herein)
d = perpendicular distance from the bottom surface of the respective groove to the inner surface of the outer tubular member.

13. A method according to any of claims 1 to 12, in which the or each explosive charge is annular.

14. A method according to any of claims 1 to 13, in which the radial expansion of the inner tubular member is not more than one quarter of the initial outside diameter thereof.

15. A method according to any of claims 1 to 14, in which the inner and outer tubular members are coaxial.

16. A method according to any of claims 1 to 14, in which the inner and outer tubular members have parallel axes.

17. A method according to any of claims 1 to 16, in which at least one of the tubular members is of a ductile material.

18. A method according to any of claims 1 to 17, in which the or each predetermined location is submerged in a liquid and any liquid present in the annular space at the or each predetermined location is substantially expelled prior to detonation of the or each charge.

19. A method according to claim 18, in which the or each annular space is sealed prior to expelling said liquid.

20. A method acording to claim 19, in which said liquid is expelled by gas displacement.

21. A method according to claim 20, in which said gas is injected through an inlet port penetrating said outer tubular member.

22. A method according to claim 19, 20 or 21, in which the annular space is sealed by an inflatable seal.

23. A method according to any of claims 18 to 22, in which the inner tubular member is a marine pile and the outer tubular member is a jacket leg of a marine structure.

24. Apparatus for explosively forming at least one circumferential joint between two tubular members disposed one within the other, which comprises an elongate member having thereon at least one annular carrier, the or each said carrier being constructed and arranged to carry an annular explosive charge for insertion into the movement along the inner tubular member, and means for centralizing the or each annular carrier in the inner tubular member, both in the respective operative position for explosive forming and during movement along the inner tubular member.

25. Apparatus according to claim 24, in which the or each annular carrier is connected to the elongate member by a plurality of struts.

26. Apparatus according to claim 24 or 25, which also comprises a detonator on the or each annular carrier.

27. Apparatus according to any of claims 24 to 26, which further comprises means for indicating the position of the or each annular carrier in the inner tubular member.

28. Apparatus according to claim 24, substantially as described herein with reference to the accompanying drawings.

29. A method according to any of claims 1 to 24, in which the or each explosive charge is located at the respective predetermined location by means of apparatus according to any of claims 24 to 28.

30. A method according to claim 1, substantially as described herein with reference to the accompanying drawings.

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